Complementary RANS and LES Computations for DDG-51 and Transition to DD-21 Acquisition

DoD Challenge Project: Time-Domain Computational Ship Hydrodynamics

E.P. Rood
Office of Naval Research
Arlington VA 22217

Abstract

A grand challenge for computational fluid dynamics is the modeling and simulation of the time evolution of the fully nonlinear turbulent free-surface flow around surface ships. This paper reports on the DoD Challenge Project team progress toward the goal of predicting the hydrodynamic flow for the DDG-51 maneuvering in waves. For the first time, Large-Eddy-Simulations (LES) describing the time-varying flow are related to Reynolds-Averaged Navier-Stokes (RANS) computations for the mean free surface flow around a surface ship, the DDG-51. As a result, new procedures are forthcoming for design analysis for hydrodynamic signatures, and the computational methods are being used in the acquisition process for the Navy's new destroyer, the DD-21. At the same time, progress continues in predicting the details of the flow for the DDG-51 in waves, and in modeling the generation of spray in the bow sheet. The importance of the HPCMP in providing the resources to meet this goal, and the rationale for particular hardware and software approaches to solving the problem are described.

Introduction

A grand challenge for computational fluid dynamics is the modeling and simulation of the time evolution of the fully nonlinear turbulent free-surface flow around surface ships. This challenge has been accepted by a DoD Challenge Project team, and the progress is presented in this paper. The technical approach of the project is to apply a suite of developed computational methods to the prediction of the microscale and macroscale time-dependent hydrodynamic motions for the DDG-51, the Navy's newest surface combatant. The suite of computational methods has been developed by F. Stern (University of Iowa), E. Paterson (Iowa Institute of Hydraulic Research), D. Dommermuth (Science Applications International Corporation), and D.K.P. Yue (Massachusetts Institute of Technology). Together, they model and simulate the turbulent free-surface hydrodynamic flow using unsteady Reynolds-Averaged Navier-Stokes equations, or RANS (CFDSHIP-IOWA); body-force level-set Numerical Flow Analysis (NFA); and Large Eddy Simulation, or LES, (SHIPLES) representations of the equations of motion for incompressible flow. Application of this suite of software codes provides mutually supportive information covering the range of scales from turbulence to ship maneuvering.

The product in the year 2000 will be a numerical representation of the combatant DDG-51 turning in waves. The validation of this numerical capability will be sufficient to provide design and analysis information for future ships especially the SC-21 family. Such computations would be used to interrogate sparse experimental databases and to extrapolate model-scale data to full scale for performance and signature design and analysis. The impact on the DoD community is the first ever capability for 1) computational hull form design to reduce ship turbulent flow hydrodynamic signatures, 2) realistic modeling and simulation capability for development of counterweapons and countermeasures, such as the anti-torpedo torpedo, and 3) roll damping coefficients for a ship underway for inclusion in standard ship motion design tools.

The technical challenge undertaken by this project requires the solution to unique and fundamental problems in fluid mechanics. These include the understanding, modeling and simulation of: free-surface turbulence, free-surface and body juncture turbulent flow involving dynamic contact lines, unsteady flow separation and moving separation lines, breaking waves and spray, and effects of surfactants on the free surface. The computational requirements pose a unique challenge to large-scale computations, including scalability and efficiency for the parallelized approach to solving the problem.

Computer Resources

Application of the computational methods to the time dependent flow around the DDG-51 has produced a history of rapid improvement in the quality and usability of computational results as new resources have been made available to the user. This project was initiated with specific computers in mind, which generally mirrored the serial computers used to originally develop the codes. Development and application of the parallelized versions of the code have occurred at the same time that advanced resources have been made available. The reader is referred to previous papers (Rood, 1997; Rood, 1998a) for details on the evolution of the nature of the resources used during the two years previous to this past year.

CFDSHIP-IOWA is a general-purpose research code that solves the unsteady RANS equations in either time-accurate or steady-flow modes. It has a data structure designed to permit either serial or parallel execution, provide a high-level of portability, and ease subroutine development (e.g., turbulence, two-phase, stratification models) by the user community. For parallel computing, a coarse-grain parallel multi-block approach and Message Passing Interface (MPI) are used. Switching between serial and parallel modes is accomplished through the use of C pre-processor statements. Excluding I/O subroutines, MPI statements are confined to the main program and block-to-block communication subroutines. A NAVO PET Tiger Team collaboration (Paterson and Sinkovits, 1999) successfully accelerated the development of CFDSHIP-IOWA.

In Paterson and Sinkovits (1999) it is shown that CFDSHIP-IOWA shows near linear acceleration, up to 64 processors, on both the SGI Origin 2000 and the Cray T3E. However, the Origin 2000 has been the target development platform for the following reasons. Foremost, the Origin is uniquely suited for the coarse-grain parallelism found in CFDSHIP-IOWA. Secondly, in comparison to the T3E, the Origin is in less demand. Finally, cache optimization was performed for the Origin. Also, it should be noted that CFDSHIP-IOWA efficiently runs on the Cray T90 (i.e., approx. 350 MFLOPS) which has been heavily used during the IIHR group training and transition to the Origin.

Problems encountered for unsteady RANS are primarily due to grid generation, domain decomposition, and load balancing. Coarse-grain parallel multi-block requires that the grid system be partitioned into blocks of equal size. Unfortunately, geometries such as the DDG-51 are difficult to grid and often require multiple blocks of disparate size to resolve geometric features and/or maintain adequate grid quality. Until algorithms can be developed for dynamic and automatic load balancing (e.g., hybrid MPI/OpenMP multi-level parallelism), the approach is to use static load balancing, i.e., burden is placed on the user generating the grid to set all blocks to nearly the same size. This procedure requires substantial time by an expert (thus the need for T90 time for use by junior investigators). Currently, static load balancing via pre-processing tools is used to partition the grid, and input files for boundary conditions and problem dimensions, into roughly equally sized sub-blocks.

The NFA code uses a two-phase LES model of the Navier-Stokes equations to simulate spray and turbulent wakes. NFA is written in High Performance Fortran (HPF), and is currently running on the NAVO T3E. The core solver of NFA uses multigrid and line Jacobi iteration to solve a Poisson equation that has variable coefficients. The CPU times for various grid sizes are provided in Table 1.

Grid Points	Cray T3E Nodes				
	8	16	32	64	128
262,144	7.7	5.0	3.8	3.8	5.8
2,097,152	--	25.8	14.7	9.4	9.2
16,777,216	--	--	96.4	50.8	30.7

Table 1. CPU seconds required to solve Poisson's equation.

Three different grid sizes are considered: 64^3, 128^3, and 256^3 grid points. The CPU times are based on solving a Poisson equation with variable coefficients to machine accuracy. As the number of CPU nodes increases for a fixed grid size, performance eventually degrades due to communication costs, but only for problems where the grid size is small compared to the number of nodes. For a fixed number of CPU nodes, the communication costs are significantly reduced (on a relative basis) as the number of grid points are increased. As a result, for 32 cpu nodes, it takes much less than eight times longer to solve the 128^3 problem than the 64^3 problem. A significant finding is that the amount of memory may be more important than the number of processors for achieving very large computations. Improvements to the core solver are currently being pursued in collaboration with a Tiger team located at the University of California at San Diego. Some of this work is the implementation of key parts of NFA in MPI.

Recent upgrades to NFA include a new procedure for initializing simulations of spray sheets and turbulent wakes. The gridding has also been upgraded to allow variable mesh spacing. In addition, recent upgrades to the Portland Group HPF compiler made it possible to rewrite the multigrid solver using recursive subroutine calls, which greatly simplified the source code. As a result, NFA will be much easier to maintain.

The SHIPLES code is used on the IBM-SP2 (ASC) to take advantage of the single node computational speed and the highly scalable distributed memory archtecture. Data decomposition is used to realize highly optimized algorithms. Computations on the IBM-SP2 permit a very large number of nodes and allow for memory per node O(1GB). The SHIPLES program is a coarse-grained data decomposition which is highly efficient on distributed memory systems. Additionally, MPI extrinsics have been built for an iterative SOR Poisson solver and an array transpose routine to be coupled with parallel codes generated by the FORTRAN parallelization utility xHPF (Applied Parallel Research, Inc.). This recent work has allowed further refinement of the SHIPLES code and accounts for a large portion of the increased efficiency of already optimized codes.

Code	Processrs	Memory	Communications	Note
CFDSHIP-IOWA	1-128	2GB-5GB	MPI	
NFA	64-256	300MB/node	HPF	Portions to MPI
SHIPLES	256	1000/node	HPF/MPI	

Summary of Research to Date

This Challenge Project began in late 1996 with the long term goal of producing computational methods with high spatial and temporal resolution for the surface ship combatant hydrodynamics in order to meet a perceived signatures requirement. The perceived requirement has had a profound impact on applications of naval hydrodynamics, necessitating a change in focus from macroscale performance (e.g., drag and powering) to microscale flow feature definition. In 1996, whereas the equations of motion were understood, the ability to solve those equations was only a dream. Massive computational capability and the expertise to wisely use that capability has grown exponentially during the past couple of years. Today computations are frequently made for complex ship geometries.

The SHIPLES code has been employed to investigate the detailed physics of the large scale unsteadiness inherent in the turbulent flow around the DDG-51. Figure 1 shows values for the time average and the fluctuating enstrophy, or vorticity magnitude squared, at the free surface for the flow around the DDG-51. The enstrophy is nearly the value for the component of the vorticity normal to the free surface, and hence portrays the whirls and eddies in the flow around the ship. The location of the free surface in the figure is the average value over time. In both the computation and the physical flow, the vorticity and the free surface are fluctuating in time on account of the passage of large scale flow structures, or “whirls”. Whereas the RANS computations produce the average flow as determined by a time average longer than the turbulence time scales, and in some cases an unsteady flow such as that produced by rolling or turning, the LES computations capture the detailed spatial and temporal evolution of the locally unsteady flow produced by turbulence. The objective of this project is to produce consistent RANS and LES computations that link the turbulent eddies to the momentum driven flow modeled by the time average flow.

Figure 2 shows computations for the hydrodynamic flow around the DDG-51 in steady speed using CFDSHIP-IOWA in parallel mode on the Origin 2000. These steady flow results will be used to compare flow statistics with the computations using SHIPLES. The objective is to show that the inherently unsteady turbulent flow computed by the LES method produces a time average flow predicted by the steady RANS computaions. The steady RANS computation required two wall-clock hours using 52 processors and achieved a computational rate of 2.1 GFLOPS.

Figure 3 shows computations using unsteady RANS for the DDG-51 in head seas. Preliminary results were shown in a previous paper. These results were obtained with the full parallel version of CFDSHIP-IOWA (v. 3.0), and are high resolution and quite efficient.

Recently revised versions of the NFA code were delivered to the Naval Coastal Systems Center (NCSC) where it is used to develop counter measures against wake-homing torpedoes. NFA is currently being used to study the turbulent wake of a Naval combatant in stratified and unstratified flows. NFA is also being used to study the onset of spray for free and wall-bounded sheets of water. The results of the numerical simulations are being compared to spray experiments that are currently being performed at the Naval Postgraduate School in Monterey. Some of the preliminary computations are shown in Figure 4. The figure shows both computations and experimental measurements of the droplet formation on the bow sheet. This flow has previously been neglected in fluid dynamics research largely on account of the difficulty in making either computations or measurements. New technologies, such as supercomputers, have made such studies possible. The flow is characterized by the no-slip condition at one boundary, and the constant pressure condition on the opposite boundary. The goal in this program is to characterize the droplet formation by the bow sheet.

Transition to DD-21

The software developed under this Challenge Project is being applied to revolutionary new hull geometries being investigated as technology options for the Navy's newest destroyer, the stealth ship DD-21, a land attack destroyer. The performance specifications for this ship have required analytic investigations of the flow using computational ship hydrodynamics. Under the "ONR Surface Ship Accelerated Hydrodynamics S&T Initiative" the software will be numerically verified, validated with towing tank tests, and delivered in the form of documented solutions for each of several novel hull forms. Although the initiative has only recently been implemented, CFDSHIP-IOWA has been applied to an example computation and is shown in Figure 5. Using 24 processors on the Origin 2000, this 0.7M grid-point simulation was computed in less than 8 hours. This short turnaround is critical for practical design and analysis. One consequence is that the competing shipyards for the DD-21 award have asked to receive the products from this Challenge Project, and a collaborative effort to implement the software in concept definition has been undertaken by the "ONR Surface Ship Accelerated Hydrodynamics S&T Initiative". The wave-piercing bow, tumblehome profile, and buttock-flow stern of this geometry, features intended to minimize flow disturbances, present unique challenges from the perspectives of gridding and resolution of flow separation.

References

Paterson, E.G., and Sinkovits, R.S., "Performance, Scalability, and Portability of a MPI-based version of CFDSHIP-IOWA: Results of a NAVO PET Tiger-Team Collaboration," *Proceedings of the 9th DoD HPCMP Users' Group Meeting*, Monterey, CA, 1999.

Rood, E.P., "Time-Domain Computational Ship Hydrodynamics", *Proceedings of the DoD HPCMP Users' Group Meeting*, San Diego, 1997.

Rood, E.P., " Time-Domain Computational Ship Hydrodynamics: Features of the Flow Around the DDG 51", *Proceedings of the DoD HPCMP Users' Group Meeting*, Houston, 1998a.

Additional Challenge Project Publications

Chen, B. and Stern, F., " Computational Fluid Dynamics of Four-Quadrant Marine-Propulsor Flow," ASME Symposium on Advances in Numerical Modeling of Aerodynamics and Hydrodynamics in Turbomachinery," Washington D.C., 21-25 June 1998.

Dommermuth, D.G., Schlageter, E.A., Talcott, J.C., Novikov, E.A., & Wyatt, D.C., “Numerical Simulation of Bow Waves and Transom-Stern Flows”, *Twenty-Second Symposium on Naval Hydrodynamics*, National Academy Press, 1998.

Paterson, E.G., Kim, J., and Stern, F., “Unsteady RANS Simulation of an Integrated Marine Propulsor,” Proc. 7th International Conference on Numerical Ship Hydrodynamics, Nantes, France, 1999.

Paterson, E.G., Wilson, R.V., and Stern, F., “CFDSHIP-IOWA and Steady Flow RANS Simulation of DTMB Model 5415,” 1st Symposium on Marine Applications of Computational Fluid Dynamics, McLean, VA, 19-21 May 1998.

Rhee, S.H. and Stern, F., "Unsteady RANS Method for Surface Ship Boundary Layers and Wakes and Wave Fields," 3rd Osaka Colloquium on Advanced CFD Applications to Ship Flow and Hull Form Design, Osaka, Japan, 25-27 May 1998, pp. 67-84, IIHR Reprint #1328.

Rood, E.P., "Transient and Periodic Turbulent Hydrodynamic Flows for Surface Ships: A DoD Challenge Project Milestone", AIAA Paper 98-2931, 1998b.

Stern, F., Wilson, R., Coleman, H., & Paterson, E., Verification and Validation of CFD Simulations, *Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference*, FEDSM99-6913, 1999.

Sreedhar, M. and Stern, F., "Non-Linear Eddy-Viscosity Turbulence Modeling for Solid/Free-Surface Juncture Boundary Layer and Wake," ASME Forum on Numerical Modeling of Free Surface and Interface Fluid Dynamics, Vancouver, Canada, June 1997, IIHR Reprint #1257.

Sreedhar, M. and Stern, F., "Investigation of Developing Juncture Flows using Large Eddy Simulation," First AFOSR International Conference on DNS/LES, Louisiana Tech University, Ruston, Louisiana, 4-8 August 1997, pp. 417-424, IIHR Reprint #1326.

Sreedhar, M. and Stern, F., "Prediction of Solid/Free-Surface Juncture Boundary Layer and Wake of a Surface-Piercing Flat Plate at Low Froude Number," ASME J. Fluids Eng., Vol. 120, June 1998, pp. 354-362, IIHR Reprint #1314.

Sreedhar, M. and Stern, F., "Large Eddy Simulation of Temporally Developing Juncture Flows," Int. J. Num. Meth. Fluids,Vol. 28, No. 1, 15 July 1998, pp. 47-72, IIHR Reprint #1323.

Wilson, R., Paterson, E., and Stern, F., "Unsteady RANS CFD Method for Naval Combatant in Waves," *Twenty-Second Symposium on Naval Hydrodynamics*, National Academy Press, 1998.

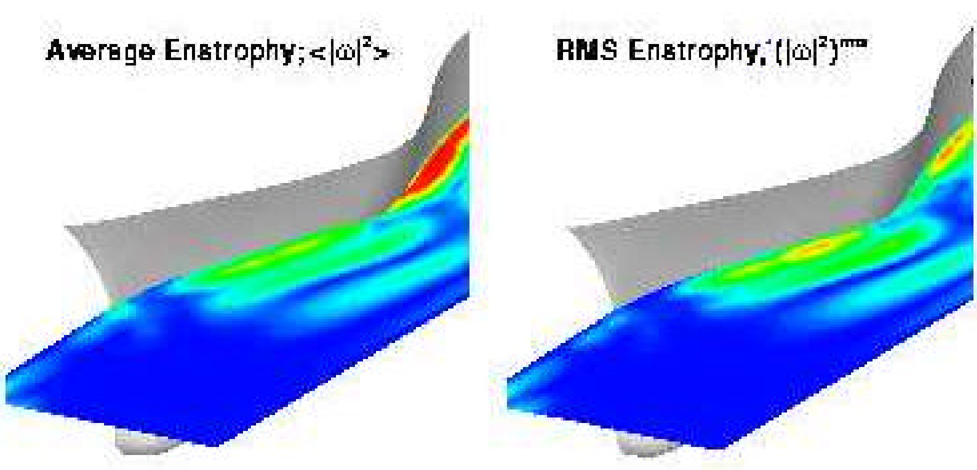
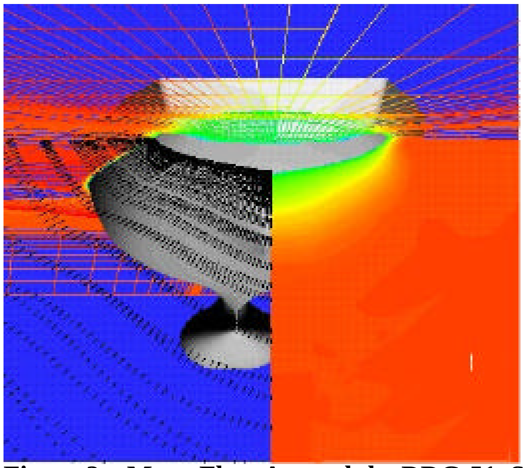


Figure 1 - Time Average and Fluctuating Surface-Normal Vorticity for the Flow Around the DDG-51 (*SHIPLES*)



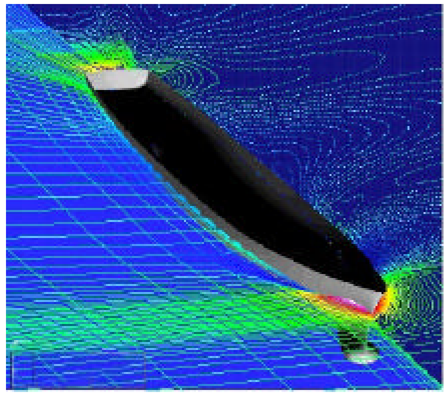
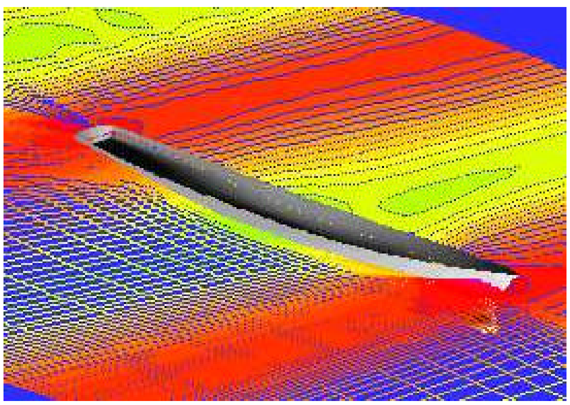


Figure 2 – Mean Flow Around the DDG-51, Showing the Crossflow and the Longitudinal Velocities (left) and the Free Surface Elevations (right) (*CFDSHIP-IOWA*)



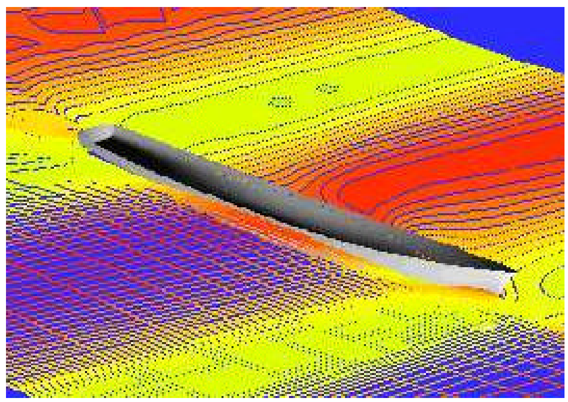
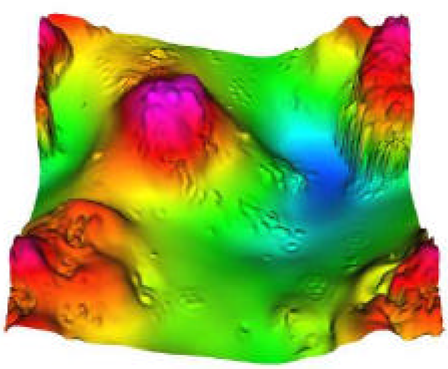


Figure 3 – Unsteady RANS Computations of the Free Surface Elevations Around the DDG-51 in Head Seas (*CFDSHIP-IOWA*)



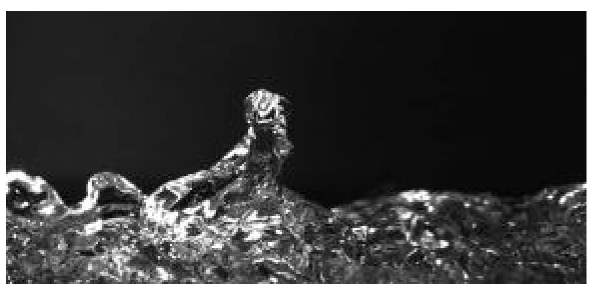
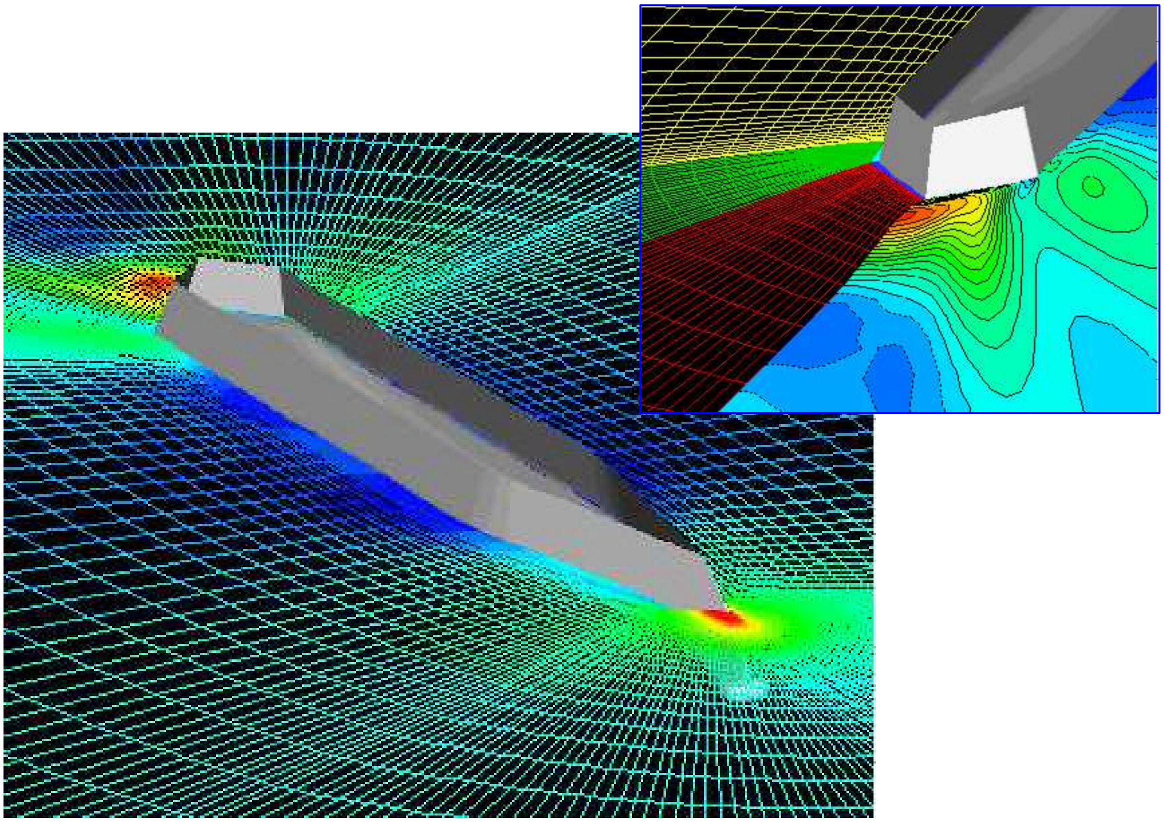
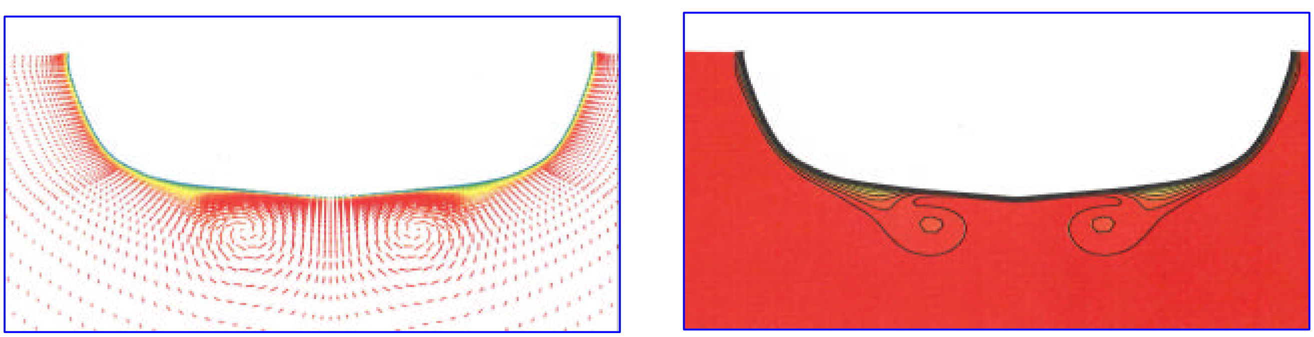


Figure 4 – Formation of Spray Droplets in Spray Sheet at Bow of Ship; Computation (isometric view) on left and Experiment (cross-section view) right (*NFA*) (photo courtesy of T. Sarpkaya, NPGS)



a) Free surface deformations



b) Cross flow and Longitudinal Flow Produced by Bow Vortices

Figure 5 – Free-Surface Flow Around a Conceptual Hullform for the DD-21 (*CFDSHIP-IOWA*)